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Research article

Second life batteries lifespan: Rest of useful life and environmental analysis

Lluc Canals Casals[a,b,*], B. Amante García[a], Camille Canal[c]

[a] C\Colom 11, Edifici TR5, ESEIAAT, 08222, Terrassa, Spain
[b] IREC, Institut de Recerca en Energia de Catalunya, Sant Adrià de Besòs, Spain
[c] ENSIACET, Tolouse, France

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ABSTRACT

Road transportation is heading towards electrification using Li-ion batteries to power electric vehicles offering eight or ten years' warrant. After that, batteries are considered inappropriate for traction services but they still have 80% of its original capacity. On the other hand, energy storage devices will have an important role in the electricity market. Being Li-ion batteries still too expensive to provide such services with economic profit, the idea to reuse affordable electric vehicle batteries for a 2nd life originated the Sunbatt project, connecting the automotive and electricity sectors. The battery reuse is, by itself, a path towards sustainability, but the cleanliness of energy storage also depends on the electricity generation power sources and the battery ageing or lifespan. This paper analyses the rest of useful life of 2nd life batteries on four different stationary applications, which are: Support to fast electric vehicle charges, self-consumption, area regulation and transmission deferral. To do so, it takes advantage of an equivalent electric battery-ageing model that simulates the battery capacity fade through its use. This model runs on Matlab and includes several ageing mechanisms, such as calendar ageing, C-rate, Depth-of-Discharge, temperature and voltage. Results show that 2nd life battery lifespan clearly depends on its use, going from about 30 years in fast electric vehicle charge support applications to around 6 years in area regulation grid services. Additionally, this study analyses the day-to-day emissions from electricity generation in Spain, and states that grid oriented energy storage applications will hardly offer environmental benefits in the nearby future. On the other hand, applications that go by the hand of renewable power sources, such as self-consumption applications, are much more appropriate.

1. Introduction

The entrance of Electric and Plug-in Hybrid Electric Vehicles (EV and PHEV respectively) into the transportation sector is seen as an environmental opportunity to advance towards a cleaner world (Hawkins et al., 2013). However, this opportunity may succeed only if electricity is generated using friendly environmental technologies such as renewable energy generators (Nordelöf et al., 2014).

On the other hand, many renewable energy sources do not offer a constant and completely reliable power supply, subjected to weather and season conditions (Beltran et al., 2012). To ensure reliability, energy storage devices are foreseen as a solution to store energy during overproduction periods and to deliver it when energy production is below load demand (Heymans et al., 2014).

There are different types of energy storage systems, such as super capacitors, flywheels, batteries, compressed air energy storage (CAES) and pumped hydro with different properties and costs. According to (Dunn et al., 2011) lithium-ion batteries are the system that has a wider application range with longer lifespan in comparison to lead acid or nickel based batteries. Moreover, their efficiency rates are close to 95% and they have almost no energy losses when they are not in use. Flywheels would also be a natural competitor against batteries, as they have similar power and amount of energy to store, but they have lower efficiency and, as they are based on kinetic energy, its installation on high energy systems is difficult as higher energy means bigger, faster and heavier moving parts. On the other hand, supercapacitors have much more power but with clearly lesser capacity and CAES or pumped hydro are best suited for high energy applications with slow response requirements.

However, with an actual cost in the range of 300–500 €/kWh, lithium-ion batteries are still too expensive to be deployed massively in stationary applications, letting space to other technologies such as sodium-sulphur batteries for big installations (KuB et al., 2016) even though these batteries should work at high temperature (above 250 °C), which make them not so interesting for automotive or home applications. An expected battery price for stationary applications that would

* Corresponding author. C\Colom 11, Edifici TR5, ESEIAAT, 08222, Terrassa, Spain.
E-mail addresses: lcanals@irec.cat (L.C. Casals), beatriz.amante@upc.edu (B. Amante García).

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begin to offer interesting revenues should go below 200 €/kWh. Thus, its deployment into the electricity grid is slow, similarly to what happens with electro-mobility. This high price is also what makes research go some steps further, looking for promising alternatives such as Lithium Sulphur batteries that have a theoretical specific energy of 2600 Wh/kg, which is 5 times higher than Li-ion, and a clearly lower price. However, they are still in an embryonic state, having quite lower power density (almost half of Li-ion), severely higher self-discharge (10 times faster), the re-apparition of memory effects and a really low cycle life (of about 50 cycles in contrast to the more than 1000 cycles of Li-ion) (Benveniste et al., 2018). Thus, Li-ion are still the best choice in many cases.

However, because of the internal chemical reactions occurred in the anode, cathode and electrolyte, Li-ion batteries lose capacity with time and use (Barré et al., 2013). For instance, they are considered not appropriate for traction purposes when they reach between an 80-70% of its initial capacity (Wood et al., 2011), (Podias et al., 2018). At this moment, batteries might be removed from the vehicle and recycled, adding costs, waste and environmental burdens to its life cycle.

Although this may seem a drawback from an EV perspective, as it means an expensive battery replacement that may be a hard to face for customers and possibly it shortens the EV useful life, it arouses some expectations in the electricity sector due to the fact that, in order to improve the EV competitiveness, car manufacturers foresee a second life of these EV batteries offering them as affordable energy storage systems for stationary applications.

These lower price batteries are supposed to bring business opportunities to renewable energy sources that see in batteries a good alliance (Kundu et al., 2015), converging to post fossil carbon societies. Consequently, a first step or sub-cycle towards a circular economy starts with the second use of EV batteries before recycling, as depicted in Fig. 1, which supposes an enlargement of the battery useful life and a reduction of its impact per kWh exchanged (Canals Casals et al., 2017a).

But there is always a question that remained unanswered by many EV battery 2nd life industrial projects (Podias et al., 2018), that is: For how long will these batteries last? The answer to this question is the purpose this study.

This paper begins with a brief description of the Sunbatt project, being this study part of its research results. Then, the study describes the selection criteria of four different stationary applications for 2nd life EV batteries, which are: Support to EV fast charge, self-consumption, area regulation and transmission deferral. Afterwards, the study analyses the rest of useful life (RUL) of PHEV and EV 2nd life batteries taking advantage of an equivalent electric battery-ageing model that simulates the battery capacity fade through its use. This model runs on Matlab and includes several ageing mechanisms, such as calendar ageing, C-rate, Depth-of-Discharge (DOD), temperature and voltage (Barré et al., 2013). Finally, this study presents an overview of environmental benefits or drawbacks obtained from these four applications, stating that, from and environmental perspective, batteries are pointless if they do not go by the hand of renewable power sources.

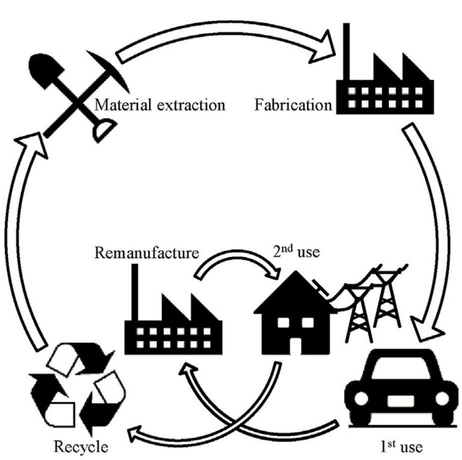

Fig. 1. Circular economy of re-used batteries.

2. Material and methods

From a technical perspective, energy storage devices in complex systems have been widely studied and implemented in demonstrative storage projects all over the world showing good performance and robustness (Rastler, 2010).

Similarly, considering the specific case of 2nd life EV batteries, major car manufacturers together with electricity utilities or power electronic companies launched several projects showing the capabilities of 2nd life EV batteries to offer residential, grid or support to renewable energy generation services among others (Reinhardt et al., 2016).

The main goal of the Sunbatt project is to offer an affordable, transportable, safe, replicable, versatile and reliable in time energy storage product based on reused EV and PHEV batteries. This ensemble of characteristics is what makes this project unique.

Responding to the first five characteristics and having in mind the environmental benefits of reuse in sustainability, the project developed a modified second-hand maritime container enclosing all the electric and electronic equipment. To smooth and prevent extreme working temperatures that may affect battery ageing and safety, the container is thermally isolated and incorporates a cooling/heating system (HVAC Heating, Ventilating and Air Conditioning in Fig. 2).

The Sunbatt container (Fig. 2) is connected to a solar carport with 8 kW generation power, to three EV chargers, to a fast EV charger and to the local electricity grid, which is able to offer 90 kW peak power, involving the electricity sector (with generation and demand control) and the transportation sector (with EV chargers and batteries) in the same project.

Four PHEV batteries, like the ones used in commercial electrified Volkswagen models, are used in the Sunbatt project. Their initial available energy, when new, was of 8.8 kWh each and a working State of Charge (SOC) range that goes from 95% to 10% defined by the car manufacturer. These batteries count on a water-glycol refrigeration system that controls their temperature. Energy is retrieved or returned to batteries using two AC/DC regulators or converters of 20 kW peak power each. Both regulators can connect to any battery, being able to work with the same battery simultaneously offering 40 kW peak power. The helm-driver of all the equipment is a Supervisory Control And Data Acquisition (SCADA), which is the one giving the orders and receiving the information of all active elements. Above it, an Energy Management System (EMS) is in charge of doing the energy, cost and emissions optimization giving the functional requirements to the SCADA. The EMS gathers all the information from critical elements inside and outside the container. That is, from meteorological forecasting, grid operators and, in this particular case, from the client that can interact and force particular use cases by means of a Human Machine Interface (HMI). A computer (PC in Fig. 2 down) works as a gateway translating CAN messages from batteries to TCP/IP communication protocol used by the SCADA and converters and, at the same time, ensures the confidential information that batteries have inside Finally an Uninterrupted Power Supply (SAI in Fig. 2 Down) was installed to proceed to controlled shutdown in case of emergency. This last element is foreseen to disappear in the following projects, being the same EV batteries capable to do this emergency shutdown function. Red lines represent power cables that connect the solar panels and batteries with the loads of EV charges and the Technical Center of SEAT (CTS). Yellow lines refer to communications of all elements in the container. Finally, blue lines correspond to the PHEV batteries' cooling system. All these elements interact with the energy storage system offering a rainbow of possible applications and it allows testing the different real case stationary

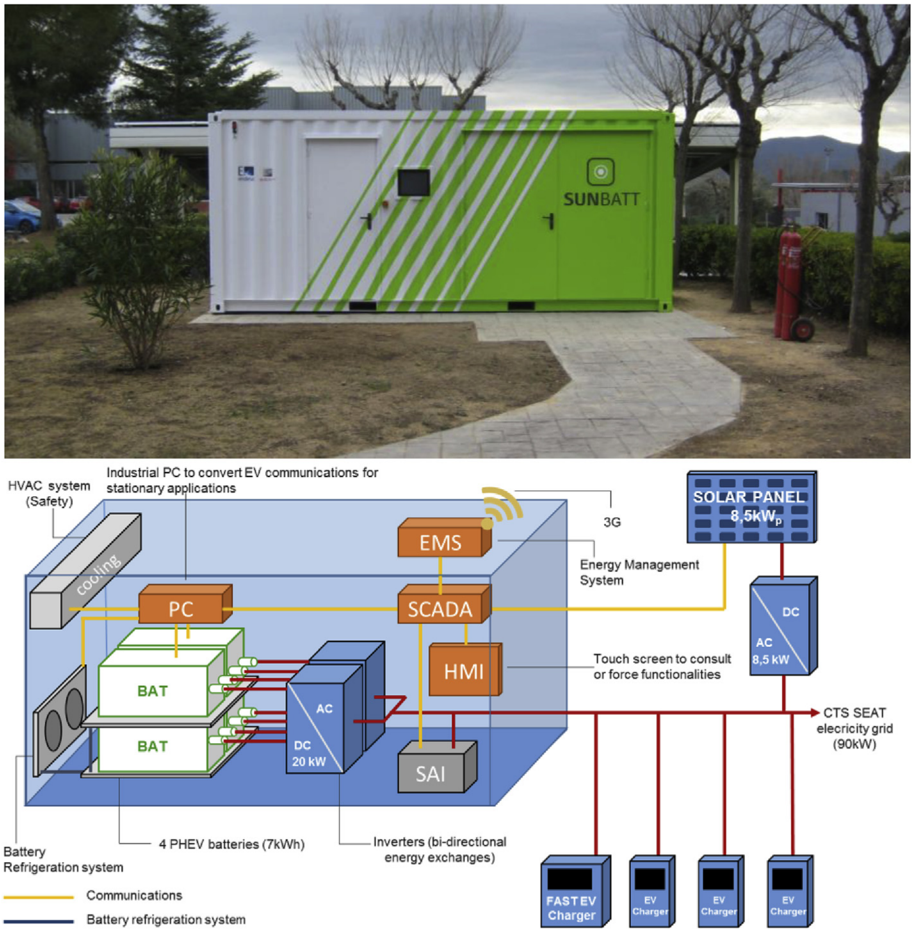

Fig. 2. Picture (Up) and schema (Down) of the Sunbatt demonstrator (Cruz Gibert et al., 2015).

applications before releasing the product into the market.

Knowing that lifetime is essential for environmental and business analysis, this study focus the attention on the last goal of the project: Reliable in time. This means that the product should respond to electricity requirements during determined periods of time. Having mentioned that batteries degrade along time and use, this paper studies battery lifespan for several stationary applications. In fact, Li-ion battery degradation differs according to the materials used in the anode, cathode, electrolyte, separator and collector and even depending on the fabrication process. The battery physical phenomena that produce ageing are, in the first place, the Solid Electrolyte Interface (SEI) formation and growth, which is a thin layer of lithium salts on the positive electrode. This layer growth has two effects: For one side, it increases the internal resistance (evolving in heat power losses) and, for another side, there is a loss of active lithium, captured within the SEI. Having less influence there are other aspects that also occur while ageing, like lithium platting, dendrite growth and cracks that may end in a puncture of the separator, gas formation, blinder corrosion, anode deformation, copper corrosion and electrolyte oxidation among others (Broussely et al., 2005).

In fact, all the aforementioned ageing phenomena occur in one way or another in most Li-ion batteries. However, its aggressiveness and occurrence can be softened in spite of battery performance loss. To reduce the potential activity, which makes ion intercalations more violent, materials can be introduced in anodes and cathodes. For example, lithium titanate (LTO) anodes within a spinel structure may replace graphitic carbon, which is the material commonly used as anode, while iron phosphate can be introduced in the cathode (LFP). These latter options offer longer lifespan and higher safety standards, which are preferable from an environmental perspective. However, the introduction of these elements reduces the voltage potential between anode and cathode, obtaining lower energy and power density batteries that is the main concern of car manufacturers that consider volume, weight and cost as prevalent aspects for battery selection (Canals Casals and Amante García, 2016). Although there is a wide variety of chemistries offering different performance characteristics, such as the higher energy or power densities from lithium nickel cobalt aluminum oxide (NCA) and lithium nickel manganese cobalt oxide (NMC) cathodes or more affordable batteries using LFP cathodes, nowadays, most EV automakers tend to select NMC cathode based batteries (Anderman, 2014), leaving a space for LFP batteries in Chinese EV models (Olivetti et al., 2017). Evidently, automakers consider battery lifespan an important aspect having 8 years warrant on their vehicles (Ahmadi et al., 2017), but once this milestone is roughly reached, it falls into a second priority level, not to mention the environmental factors.

There are two approaches to calculate batteries' lifespan: Using empiric tests or running simulations. Testing real case applications may take many years to show significant results while simulations provide faster results at lower costs and they enable testing different operation conditions or parameters. Although the Sunbatt project works in both directions, this study follows the second option to present batteries' lifespan predictions taking advantage of a validated battery electric equivalent model of these same batteries used in the project to estimate the RUL (Canals Casals et al., 2017b). These same cells are used in the Volkswagen group to build all PHEV and EV batteries, grouping them in modules of 6 or 12 cells and connecting them in series or parallel depending on the needs. In particular, they are prismatic NMC cells that have an individual capacity of 25 Ah. The electric equivalent circuit

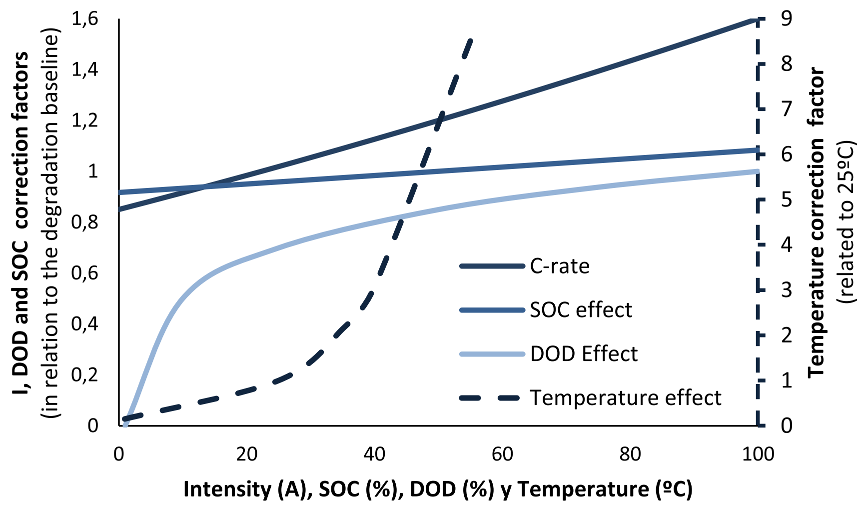

Fig. 3. Effects of the different ageing factors in relation to the baseline discharge rate at 25ºC, 1C and 100\% DOD cycles (Canals Casals et al., 2017b).

consist of a resistance (R) and 4 resistance and capacitor pairs (RC) in series. The parametrization of these components (Ri and Ci) was obtained using Electrochemical Impedance Spectroscopy method, which is more precise than other common methods, such as the pulse test (Swierczynski et al., 2013).

The model considers the ageing caused by calendar and cycling, incorporating the most relevant ageing factors such as: Temperature; SOC or voltage; DOD; Current intensity going through the battery (C-rate) and the time under each condition (Barré et al., 2013), (Vetter et al., 2005). To evaluate the ageing under different conditions, this model takes an ageing reference value per Ah exchanged from the cell considering a 1C-rate charge-discharge cycle with 100% DOD, an average SOC of 50% and a temperature of 25 °C. Then, the model modifies this ageing base value according to four correction factors (C-rate, SOC, DOD and Temperature) depending on the working conditions at every instant. The relation between the base case and the correction factors is presented in Fig. 3, were it can be appreciated that the effect of SOC is quite low in comparison to the C-rate (notice that as the cell has a capacity of 25Ah, a 1C-rate corresponds to the 25 A in Fig. 3) and that temperature follows an exponential curve while DOD's relation follows a logarithmic expression. Taking DOD to put an example of how Fig. 3 works, the reference ageing factor should be multiplied by a correction factor of 0.65 (ageing would be lower) if DOD is about 20%, while the correction factor would be 1 in the case of 100% DOD. The relations between the correction factors and the reference ageing were taken from experimental accelerated ageing tests under laboratory controlled conditions. For more details of the equations, parameters and principles of the model, the reader can take a look to the model description (Canals Casals et al., 2017b) and applications (Canals Casals and Amante García, 2017).

The main input of the model is the current load that batteries should follow for each application. The intensity through the battery model defines the variation of SOC, DOD and C-rates at every instant needed to calculate ageing. This model simulates the electric response of the battery presenting the State of Health (SOH) evolution against time. SOH is defined as the ratio between the actual capacity and the initial capacity of a battery. The End-of-Life (EoL) is defined as the SOH batteries have when they cannot fulfil the application's requirements. Therefore, the time needed to reach the EoL is the expected RUL for each 2nd life application.

The selection of the possible energy business scenarios where batteries may fit is done according to literature. The EPRI reports (Rastler, 2010) and (Akhil et al., 2013) indicated that the most economically interesting stationary applications were: Transmission (TD) and Time of Use (ToU), Deferral (benefits coming from investment deferral), area regulation and support to renewable energy generation. The approaches done by Neubauer (Neubauer et al., 2012) and Cready (Cready et al., 2003) confirmed that these economical estimations are consistent.

Additionally, the entrance of EVs in the automotive park incur into grid disturbances, especially when multiple fast charges occur (Maitra et al., 2013). Thus, batteries may provide peak shaving and energy quality services during fast EV charges. Moreover, batteries giving support to fast EV charges can store energy from renewable energy sources while, at the same time, enhance the entrance of EVs, which have a substantial potential to reduce the environmental impact from transportation.

Finally, EV and PHEV battery packs, having around 8 and 24 kWh energy, are considered ideal for residential Self-consumption installations (Andrew, 2009) as the average home energy consumption per day is around 10 kWh.

Thus, these four application are the study cases discussed in this paper in the following configurations:

- **Fast EV Charge**: The particular case studied consists of three fast EV chargers and a grid connection of 70 kW power peak. A simulation of the EV arrival and the fast charge curves overlapping indicate that 20 kW were additionally needed during short periods. This extra power is offered by 2nd life batteries instead of increasing the power supply installation (with its costs, materials and pollution associated) and paying the additional fixed tariff costs.
- **Self-consumption**: This case consists on solar panels that generate renewable energy on a building rooftop with a battery system capable to store around 6 kWh.
- **Area regulation**: This case is based on the Self-consumption application described above where, additionally, the system provides grid stability services. Area regulation is added to the Self-consumption current profile. This load addition ends up with higher amounts of energy exchange (11 kWh).
- **Transmission Deferral**: This application provides power support to a neighborhood grid transformer when the energy demand is higher than the transformer's capability. In this scenario, batteries charge during off-peak periods and deliver energy when needed. As the electricity consumption is supposed to increase in the following years, the quantity of days needing power support will gradually increase. A 20-year forecast was done obtaining a final amount of energy to store of 995 kWh per day. The benefits of this business case is expected to come, basically, from postponing the transformer upgrade.

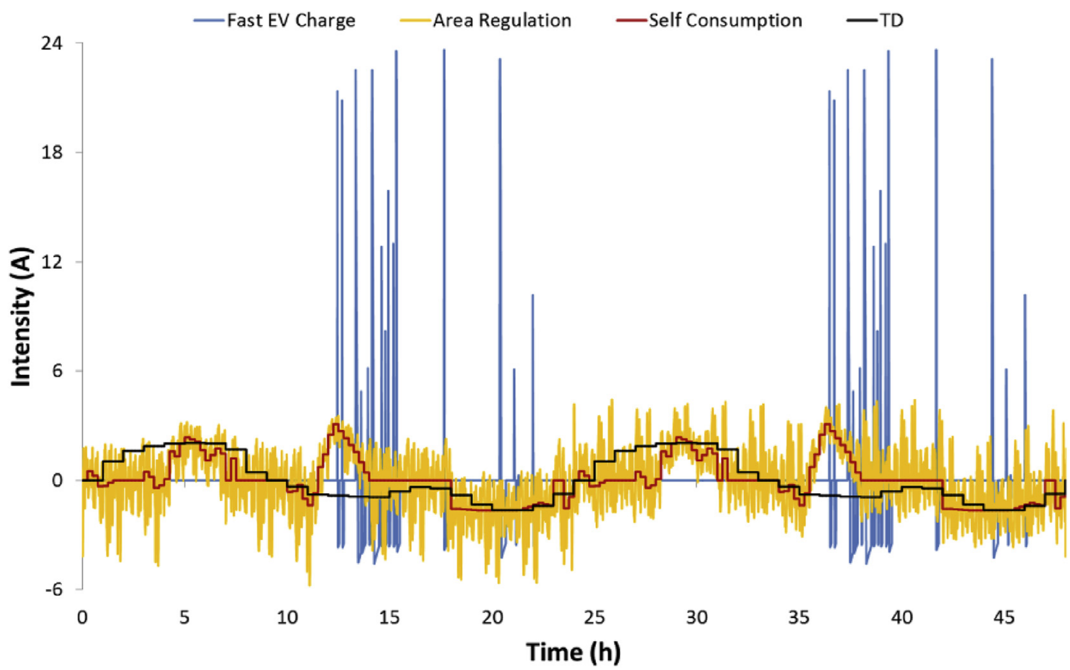

Fig. 4. Current inputs introduced to the ageing model for RUL estimation (Cruz Gibert et al., 2015).

The current going through batteries is extracted from each application's power and energy demand divided by the number of batteries they use. For example, the Fast EV charge case needs 20 kW for short periods of time with a total daily energy exchange of only 2 kWh, thus, 1 PHEV battery is enough to fulfill the requirements. Self-consumption systems need to store more than the 6 kWh, which is in the range of what one single PHEV battery can afford at the beginning of the 2nd life. However, two PHEV batteries were not enough to fulfill the needs of the Area Regulation application, which is based on the Self-consumption profile. Consequently, for both cases one EV (24 kWh) battery is used. Finally, the huge amount of energy needed for TD during the last years imposes the use of more than 200 PHEV or 80 EV batteries. Fig. 4 presents the current loads of all applications, where the Area Regulation current load (yellow) oscillates around the Self-consumption baseline (red). The black line represents the transmission deferral load for a single battery and the blue line shows the punctual and higher loads from fast charge overlapping in the EV charging station.

A constant temperature of 25 °C was considered for the four study cases analysed in this work.

Notice that none of the scenarios presented has to necessarily run with the Sunbatt container. In fact, the container has many electronic devices which were thought only for the demonstrator, as a showroom, not being necessary for a commercial version of it. The cooling system, the HMI and the UPS or SAI are some of these unnecessary elements. Moreover, the Sunbatt container had an empty space inside (to let people in to see the installation) which should be optimized. Therefore, the environmental issues of the study do not consider the container itself but an equivalent energy storage system, which would need the same power electronics using new or 2nd life batteries.

From an environmental point of view, the study discusses the supposed benefits of these four applications.

For the Self-consumption scenario, it summarizes the results from a previous study (Lluc Canals Casals et al., 2016a,b), while for the other three scenarios the study performs a day-to-day analysis of the emissions caused by the Spanish electricity generation mix during peak and off-peak hours for the years 2015 and 2016. This information is collected from the website of the Spanish regulator: Red Eléctrica Española. Then, these emissions are compared with the periods when batteries should store and return the energy according to the studied applications. Moreover, the study also considers the energy losses derived from the charge/discharge process, which has an overall efficiency of around 85% assuming that the transformer and battery efficiency are both above 95% (Musavi et al., 2012), (Kang et al., 2014) and that these losses occur either when charging and discharging.

3. Results and discussion

The model results for the four scenarios are presented in Fig. 5, showing that battery lifespan changes considerably depending on the application.

Fast EV charge support is the one presenting a longer lifespan with almost 29 years of use before reaching the EoL. It should be noticed that, normally, the EoL of a battery is considered when it has lost a 20% of the initial capacity. Consequently, as reused batteries start their 2nd life working phase at 80% SOH, the common EoL for 2nd life batteries should be fixed at 60% SOH, similarly to other 2nd life ageing studies (Heymans et al., 2014). For the fast EV charge case, the corresponding RUL ending up at 60% SOH would be 15 years. However, Fig. 5 top left shows that the battery discharge takes only around 15% SOC at the 40% SOH. Knowing that the SOC range of the analysed battery goes from 95% to 10% of the total capacity, at 60% SOH the battery still has more than 70% of the usable battery capacity. In consequence, a longer lifespan could be expected, fixing the EoL at 40% SOH for this scenario. Although the system seems to be capable to work at even lower SOH, the risk of falling into the sudden death of the battery, which is a sudden acceleration of the ageing phenomena (Martinez-Laserna et al., 2016), is yet not clearly identified as there are cells that find this ageing knee at 60% SOH and other can continue beyond this point without any trace of it (Martinez-Laserna et al., 2018). Therefore, on behalf of prudence and robustness of results, the study does not dare to go below this point.

SOH and capacity fade evolution along time for the Self-consumption scenario achieve a RUL of 11.6 years. An EoL of 40% SOH is also established for this scenario for the same reasons previously mentioned. However, in order to have comparable results with the other scenarios, this evolution shows how the 60% SOH is reached after 5.9 years of uninterrupted use, which is close to the 7 years of other studies in similar scenarios (Madlener and Kirmas, 2017). It should be mentioned

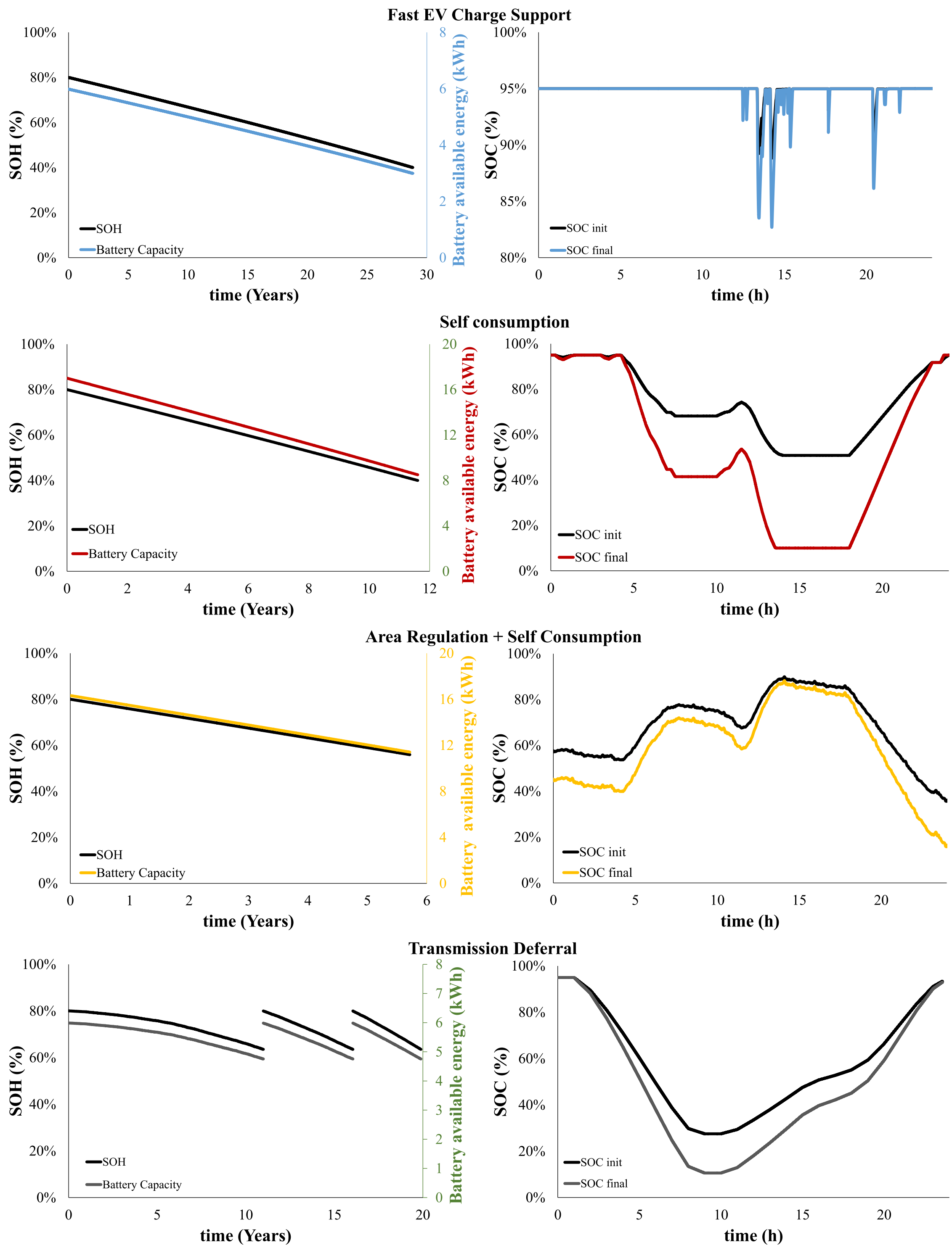

Fig. 5. SOH (left) and SOC (right) evolution of 2nd life EV batteries.

that the battery achieves its maximum DOD (85%) when it reaches the 40% SOH. In consequence, it would start to present problems to follow the load demand if the system should work beyond this RUL.

Comparing the ageing rate results between the self-consumption and the area regulation case (Fig. 5 middle), which share the same current baseline, it can be appreciated that the inclusion of the Area Regulation services over Self-consumption visibly impacts batteries' ageing. In fact, in the Area Regulation scenario, the 60% SOH is reached after 4.7 years in contrast to the 5.9 years of the Self-consumption study case, which corresponds to an 80% shorter period of time.

Comparisons between these self-consumption and area regulation applications can go further by taking into account the functional EoL, which is reached when the system demands more than the 85% DOD. For the Area regulation application, this EoL is reached after 5.7 years (corresponding to 55.9% SOH) much before the 11.6 years from the Self-consumption case (corresponding to 40% SOH). This difference is visible in the SOC curve (Fig. 5 right), where the ripples caused by the current demands from the Area Regulation are observable. If the system should work beyond this 55.9% SOH limit, the battery would miss some of the requirements at deep discharges, failing to provide area regulation services. This incapacity to provide the service would certainly revert into an economic fine by the grid operator, as it may carry grid stability problems elsewhere. Consequently, the area regulation study case reaches the EoL in less than half the time compared to the Self-consumption case. This situation exemplifies how functional requirements have a strong impact on the EoL definition, which in this case is much more than the impact of the ageing rate.

Lastly, the Transmission Deferral scenario is particularly different to the other ones because the frequency of energy demand from batteries increases every year. In fact, batteries work only 17 days during the first year while during the 20th year they do it almost all days. That is why Fig. 5 (down) shows an accelerating SOH vs time curve. To reach the 20 years forecasted for the Transmission Deferral application, results show that two battery replacement sets should be done during this period. The first pack of batteries will last almost 11 years, while the RUL of the following sets of batteries is 5 and 3.8 years respectively. The number of batteries in this study case was calculated so that the EoL at 60% SOH coincide with the whole 85% DOD range use (Fig. 5 down right).

Notice that these are simulated results from a cell model validated using several accelerated ageing tests on multiple cells. Real tests have not been performed as they would take too much years and cost to perform. Thus, there is a margin of uncertainty that should be considered. First, regarding the variability of ageing of the number of cells in the battery, that is, each battery ages relatively different than another. From a previous study (Canals Casals et al., 2016a,b), it was observed that a full EV battery reaching 80% SOH had a 3% variation, which would mean that, takin a linear projection, at the EoL (60% SOH), this variation should be around 6%. And secondly, from the precision of the model itself, that together with the cell variability would be between a 10 and 15% margin.

All the study cases end up with a battery lifespan longer than 5 years and three of them last more than 10 years before needing any replacement. This time lapse is long enough to think of these batteries as an alternative to actual lead acid batteries and other energy storage systems. Moreover considering that their expected selling price is between 40 and 150 €/kWh (Madlener and Kirmas, 2017), much less that what new Li-ion battery packs cost now or will cost in the nearby future (Coroller, 2011).

In consequence, EV batteries have still a long path to walk if 2nd life or battery reuse begins. In fact, as not all the scenarios have the same EoL, maybe batteries could go even for a 3rd life if possible, although marginal costs might not support new adaptations. Moreover, 2nd life may bring more benefits than just economic revenue, such as environmental and social consciousness-raising or circular economy enhancement.

In fact, circular economy by means of 2nd life batteries eliminates the environmental impact caused by the manufacture of new batteries with an equivalent capacity, participating in the up/downstream circles of structural construction components (Iacovidou et al., 2017). This fact should not be neglected as the manufacture of an EV battery emits around 4.000 $kgCO_2e$, which are almost half of the whole EV manufacture emissions (Notter et al., 2010). Moreover, it represents the 11% of the global warming potential of the whole EV life cycle impact considering the European electricity mix (0,421 $kgCO_2e$./kWh).

An analysis of the environmental impact of the self-consumption scenario showed that the use of solar panels for self-consumption together with batteries represent a 9% impact reduction in comparison to a common grid powered building using the Spanish electricity mix (Lluc Canals Casals et al., 2016a,b). The aforementioned study considered the power electronics environmental impact too, indicating that effect in the overall GWP is almost negligible, being the emissions during the first and second life the ones having almost all the impact, followed by the fabrication of the battery itself.

Similarly, the use of renewable power sources on batteries giving support to fast EV charges would reduce its environmental impact. However, it may not be the case if the energy is taken directly from the electricity grid as it happens in the scenario presented in this study. Under this later condition, energy is stored short after the EV charge is completed (Fig. 4) to be ready for another vehicle. In consequence, the electricity power source share of the grid would not have changed significantly and, thus, the emissions should be similar. Moreover, as mentioned in the methodology, the battery charge/discharge overall process is assumed to have an 85% efficiency. This incurs into an increase of the emissions about 17% to provide the same amount of energy.

However, there is an indirect impact related to the power plants installed in a country that should be mentioned. Power generation is related to power demand, thus, if batteries are used to reduce the instant power demand, fewer power generation infrastructure should be needed, offering the opportunity to dismantle or reduce the production of energy from more pollutant power plants. Regarding this idea, the Spanish electric system annual report (Red Electrica de España, 2016) indicates that Spain has 106 TW power pants, where renewable power sources take more than 50 TW. Curiously, the maximum instant demand of the country was roughly 40 TW, being 2015 the first year of annual energy demand increase since 2009. These values suggest that all the energy of the country could be covered by renewable power sources but, instead of that, they provided only the 42.8% of the total energy consumed. This report indicates that the maximum contribution of renewable energy generation reached a 70% in one single day of February, basically from wind at night. This is caused by the fact that renewable power sources are subjected to weather and climate conditions instead of their available power, so they do not produce what we need but what they can.

These later facts from the annual report seems to indicate that if energy is stored during low demand (valley or off-peak) periods, which occur normally at night, and consumed during high demand (peak) periods, alternatively around 12 or 22h, the emissions from electricity generation could decrease, as it happens in many countries where demand is basically covered by oil-fired plants (Holland and Mansur, 2008). To evaluate this environmental opportunity this study presents the day-to-day emissions per kWh at peak and off-peak periods in Spain on 2015 and 2016. Fig. 6 shows how this situation occurs only in 30% of the days and it presents how the average emissions due to electricity generation on Off-peak hours is 0.016$kgCO_2e$ higher than on Peak hours.

This can be partially explained when peak consumption falls in daylight hours, when solar generation may represent between a 10 and 20% of the generation of this time-frame but, curiously, this situation happens only between 33 (2015) and 37% (2016) of the days, which are additionally concentrated during summer months. During the rest of the year, the consumption peak is reached normally in the evening (around 22h), when the contribution from wind generation is generally higher than later at night. An extended analysis of the power source share to generate electricity during peak and off-peak periods is presented in Fig. 7 and Fig. 8 for the studied time-lapse (2015–2016).

The combination of Figs. 6–8 allows to observe that, generally, the difference in emissions between peak and off-peak hours is lesser when renewable power sources are more active, which seems to occur in winter, when the contribution of wind and hydraulic power sources achieve higher rates, specially in 2016. However, although in summer solar power enters noticeably into play, wind and hydraulic sources reduce dramatically their contribution. This gap is filled mainly by pollutant power plants such as combined cycle (CCG), cogeneration and coal power plants. Particularly, coal power plants reach their maximum participation share during Off-peaks periods, which explains the emissions per kWh rise.

This day to day analysis of the electricity generation mix in Spain went a little further by observing what occurs through weekdays. Table 1 presents the average of generation and emissions on Peak and Off-peak hours for each weekday along the years 2015 and 2016. At first sight, Table 1 shows that the generation during off-peak hours is

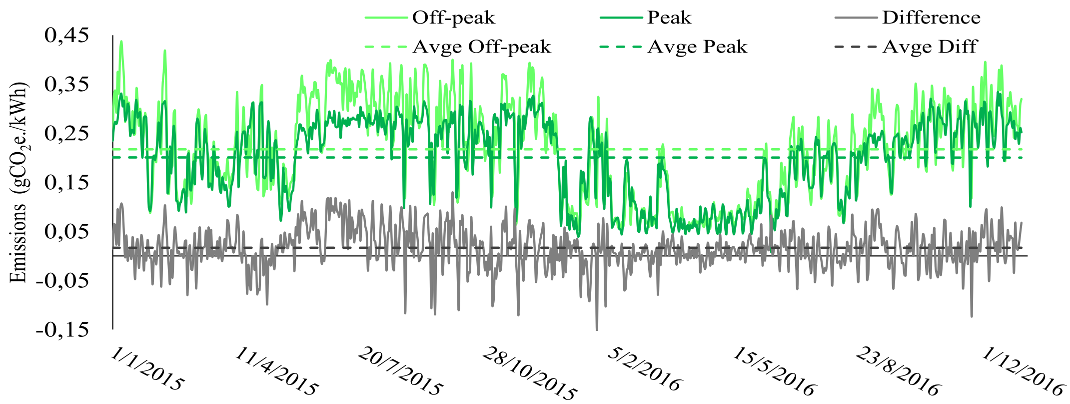

Fig. 6. GWP emissions from the Spanish electricity generation mix on peak and off-peak hours.

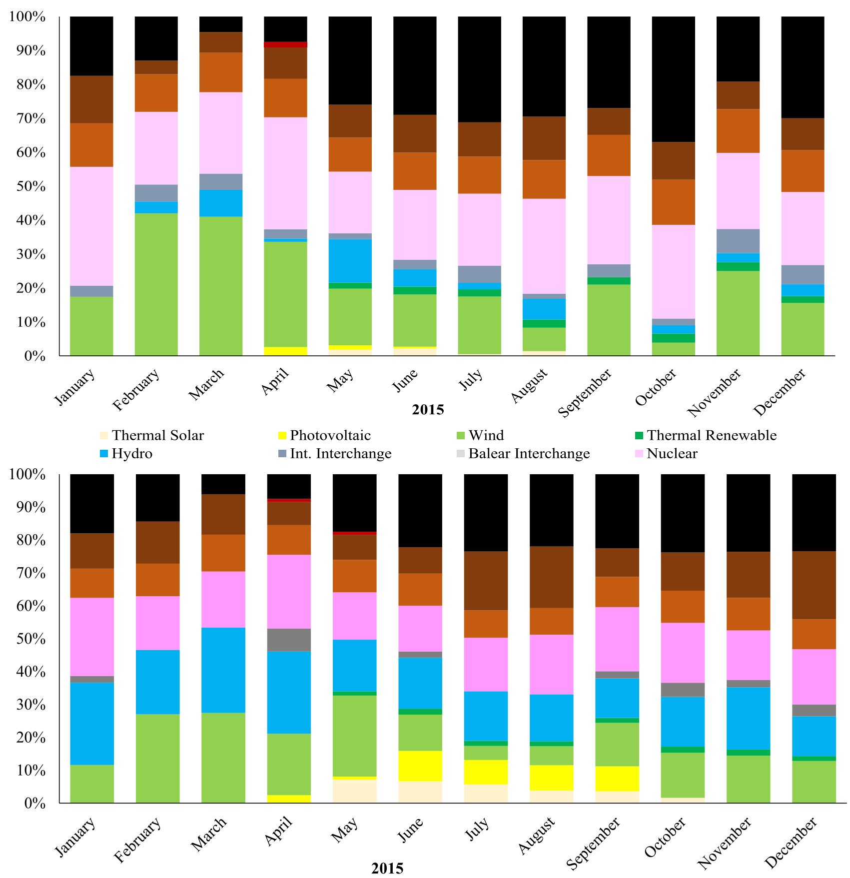

Fig. 7. Spanish power source generation share during peak (Up) and off-peak (bottom) hours in 2015.

around 2/3 of the generation during peak hours and that both, generation and emissions, are relatively higher during workable days (from Monday to Friday) than during week-ends. Results from Table 1 coincide with what was previously stated from Fig. 6, that the environmental impact of electricity generation on Off-peak hours are higher than those of Peak hours. Nonetheless, Table 1 indicates that it is on Monday when the difference between Peak and Off-peak emissions is lower or even inversed, as it happens in 56% of Mondays.

In consequence, if we expect to reduce the environmental impact of time-shifting applications, such as TD, it is necessary to clearly oversize the installation of renewable power sources, even more if we consider the 85% overall efficiency of Li-ion batteries.

On the contrary, it is hard to expect that batteries participating in area regulation services may offer any environmental benefit, as load changes are frequent and the overall efficiency of batteries has a negative impact that is difficult to overcome.

4. Conclusions

This article estimates the RUL of 2nd life EV batteries on four applications that may revert on economic and environmental benefits. Results show that the use of 2nd life EV batteries to provide power support to fast EV charge stations seems to last over 30 years, enhancing clean electro-mobility while offering solutions to fast EV charges.

Moreover, in other stationary energy storage applications such as self-consumption, battery RUL estimations show endurances close to 12 years, offering reliability to renewable electricity generation and enhancing its entrance into the market.

The other two applications studied, area regulation and transmission deferral, are grid-oriented services. For these cases, the battery

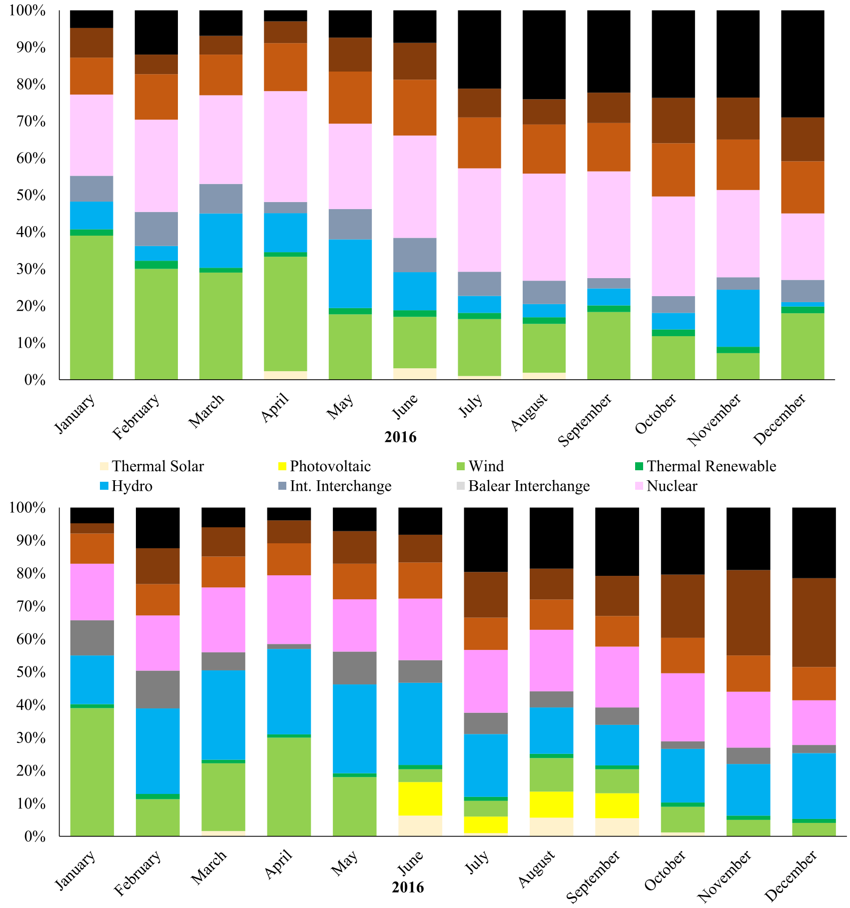

Fig. 8. Spanish power source generation share during peak (Up) and off-peak (bottom) hours in 2016.

Table 1
Average electricity generation and emissions on Peak and Off-peak hours along 2015 and 2016.

	2015				2016				Emissions
	Peak Power (MW)	Off-peak Power (MW)	Peak Emissions ($kgCO_2e.$)	Off-Peak Emissions ($kgCO_2e.$)	Peak Power (MW)	Off-peak Power (MW)	Peak Emissions ($kgCO_2e.$)	Off-Peak Emissions ($kgCO_2e.$)	Peak < Off-Peak (%)
Monday	34,360	21,513	0,241	0244	34,531	21,258	0,170	0152	56%
Tuesday	34,694	22,945	0,247	0267	35,049	22,816	0,183	0193	30%
Wednesday	34,750	23,084	0,247	0273	34,841	22,930	0,179	0190	29%
Thursday	34,331	23,057	0,249	0277	34,693	22,916	0,182	0196	32%
Friday	33,795	23,039	0,242	0281	33,873	22,824	0,171	0193	25%
Saturday	30,542	22,219	0,221	0250	33,834	22,805	0,139	0162	18%
Sunday	29,851	20,616	0,204	0222	33,980	22,868	0,132	0142	30%

lifespan estimation lasts for almost 6 and 12 years respectively. However, the environmental benefits from these grid oriented applications in Spain seems hard to achieve, as they should come from time-shifting generation and it was observed that the emissions caused by electricity generation during Off-peak hours is generally higher than those of Peak hours.

Therefore, if environmental benefits are to be reached, 2nd life applications should go by the hand of renewable power sources or they should not be used for grid services. In consequence, other business alternatives should be analysed, such as the ones related to substitute high polluting portable power generators (normally diesel/fuel generators) in emergency shutdowns or temporary events, which would fit better to the Sunbatt container.

The presented results open a window for accurate 2nd life's battery business and environmental calculations and will help the decision making to invest or not on each of the selected applications.

These results reveal the potential of 2nd life EV batteries for stationary applications, presenting them as a good alternative to new and expensive lithium batteries or less performing energy storage systems.

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